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This document has been approved for publication by the Management Council of the Consultative Committee for Space Data Systems (CCSDS) and represents the consensus technical agreement of the participating CCSDS Member Agencies. The procedure for review and authorization of CCSDS Recommendations is detailed in Reference [1] and the record of Agency participation in the authorization of this document can be obtained from the CCSDS Secretariat at the address below.

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STATEMENT OF INTENT

The Consultative Committee for Space Data Systems (CCSDS) is an organization officially established by the management of member space Agencies. The Committee meets periodically to address data systems problems that are common to all participants, and to formulate sound technical solutions to these problems. Inasmuch as participation in the CCSDS is completely voluntary, the results of Committee actions are termed **Recommendations** and are not considered binding on any Agency.

These **Recommendations** are issued by, and represent the consensus of, the CCSDS Plenary body. Agency endorsement of these **Recommendations** are entirely voluntary. Endorsement, however, indicates the following understandings:

- Whenever an Agency establishes a CCSDS-related **standard**, this **standard** will be in accord with the relevant **Recommendation**. Establishing such a **standard** does not preclude other provisions which an Agency may develop.

- Whenever an Agency establishes a CCSDS-related **standard**, the Agency will provide other CCSDS member Agencies with the following information:

  -- The **standard** itself.

  -- The anticipated date of initial operational capability.

  -- The anticipated duration of operational service.

- Specific service arrangements shall be made via memoranda of agreement. Neither these **Recommendations** nor any ensuing **standards** are a substitute for a memorandum of agreement.

No later than five years from its date of issuance, these **Recommendations** will be reviewed by the CCSDS to determine whether they should: (1) remain in effect without change; (2) be changed to reflect the impact of new technologies, new requirements, or new directions; or (3) be retired or canceled.

In those instances when a new version of a **Recommendation** is issued, existing CCSDS-related Agency standards and implementations are not negated or deemed to be non-CCSDS compatible. It is the responsibility of each Agency to determine when such standards or implementations are to be modified. Each Agency is, however, strongly encouraged to direct planning for its new standards and implementations towards the later version of the Recommendation.

FOREWORD

This document, which is a set of technical Recommendations prepared by the Consultative Committee for Space Data Systems (CCSDS), is intended for use by participating space Agencies in their development of Radio Frequency and Modulation systems for earth stations and spacecraft.

These Recommendations allow implementing organizations within each Agency to proceed coherently with the development of compatible Standards for the flight and ground systems that are within their cognizance. Agency Standards derived from these Recommendations may implement only a subset of the optional features allowed by the Recommendations herein, or may incorporate features not addressed by the Recommendations.

In order to establish a common framework within which the Agencies may develop standardized communications services, the CCSDS advocates adoption of a layered systems architecture. These Recommendations pertain to the physical layer of the data system. Within the physical layer, there are additional layers covering the technical characteristics, policy constraints, and procedural elements relating to communications services provided by radio frequency and modulation systems. Recommendations contained in this document have been grouped into separate sections representing technical, policy, and procedural matters.

These Recommendations for Radio Frequency and Modulation Systems, Part 1: Earth Stations and Spacecraft, were developed for conventional near-earth and deep-space missions having moderate communications requirements. Part 2 will be concerned with data relay satellites and will address the needs of users requiring services not provided by the earth stations covered in this document.

The CCSDS will continue to develop Recommendations for Part 1: Earth Stations and Spacecraft, to ensure that new technology and the present operating environment are reflected. New Recommendations for Part 1, which are developed in the future, will utilize the same format and be designed to be inserted into this book. Holders of this document should make periodic inquiry of the CCSDS Secretariat, at the address on page i, to make sure that their book is fully current.

Through the process of normal evolution, it is expected that expansion, deletion, or modification to individual Recommendations in this document may occur. This document is therefore subject to CCSDS document management and change control procedures which are defined in reference [1]. Current versions of CCSDS documents are maintained at the CCSDS Web site:

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At the time of the latest revision, the active Member and Observer Agencies of the CCSDS were

Member Agencies

- Agenzia Spaziale Italiana (ASI)/Italy.
- British National Space Centre (BNSC)/United Kingdom.
- Canadian Space Agency (CSA)/Canada.
- Centre National d'Etudes Spatiales (CNES)/France.
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)/Germany.
- European Space Agency (ESA)/Europe.
- Instituto Nacional de Pesquisas Espaciais (INPE)/Brazil.
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- National Space Development Agency of Japan (NASDA)/Japan.
- Russian Space Agency (RSA)/Russian Federation.

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- European Telecommunications Satellite Organization (EUTELSAT)/Europe.
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- Ministry of Communications (MOC)/Israel.
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- National Space Program Office (NSPO)/Taipei.
- Swedish Space Corporation (SSC)/Sweden.
- United States Geological Survey (USGS)/USA.

DOCUMENT CONTROL

DOCUMENT	TITLE	DATE	STATUS/REMARKS
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	January 1987	Original Issue
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	September 1989	New RF and Mod. recommendations added to Book at September 1989 Ottawa Plenary.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	June 1993	New RF and Mod. recommendations added to book at May 1992 and June 1993 Meetings. See dates in Table of Contents.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	November 1994	New RF and Mod. recommendations 2.6.7B, 2.6.8B, 3.1.4A, and 3.3.4.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	May 1996	New RF and Mod. recommendations 3.6.1, 3.6.2, 4.2.2, and 4.2.3.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	May 1997	New RF and Mod. recommendations 2.4.8, 2.4.14A, 2.4.14B, 2.4.15A, 2.4.15B, 2.4.16, and 2.4.6.B.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	June 1998	Deleted RF and Mod. recommendations 3.1.3A and 3.1.5B.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	May 1999	Adds new recommendations 2.2.7 and 2.4.12B; updates recommendation 2.4.12A.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft	May 2000	Updates recommendations 3.1.1, 3.1.2A, 3.1.6B, and 3.2.1 (changed to 3.2.1A).

REFERENCES

[1] *Procedures Manual for the Consultative Committee for Space Data Systems.* CCSDS A00.0-Y-7. Yellow Book. Issue 7. Washington, D.C.: CCSDS, November 1996.

[2] *Radio Frequency and Modulation—Part 1: Earth Stations.* Report Concerning Space Data System Standards, CCSDS 411.0-G-3. Green Book. Issue 3. Washington, D.C.: CCSDS, May 1997.

[3] *Radio Regulations*, International Telecommunication Union, Geneva, Switzerland, 1992.

[4] *Recommendations and Reports of the CCIR*, 1986 Plenary Assembly, Dubrovnik, Yugoslavia, 1986.

[5] *Radio Frequency and Modulation Systems—Spacecraft-Earth Station Compatibility Test Procedures*. Report Concerning Space Data Systems Standards, CCSDS 412.0-G-1. Green Book. Issue 1. Washington, D.C.: CCSDS, May 1992.

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2.2.4	$4000/2^n$; n = 0, 1, 2 ... 9	Range of telecommand bit rates.
2.2.5	$\pm 2x10^{-4}f_{sc}$; $\pm 1x10^{-5}$; $\pm 5x10^{-5}$	Subcarrier frequency offset and stabilities.
2.2.6	$0.98 \leq 1.02$	Symmetry of baseband modulating waveforms.
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2.2.7 MEDIUM-RATE TELECOMMAND SYSTEMS

The CCSDS,

considering

(a) that most space agencies presently utilize either 8 kHz or 16 kHz subcarriers for telecommand transmissions where data rates are less than or equal to 4kbps;

(b) that missions in the near future may require higher rates telecommanding capabilities, in the range 8 kbps to 256 kbps;

(c) that the possibility of simultaneous ranging, telecommand transmission and telemetry reception can result in optimal utilization of the Earth station coverage time;

(d) that ranging requires that a distinct carrier component be present in the up- and down-link signals;

(e) that subcarrier modulation techniques require substantially more spectrum compared to other modulation techniques;

(f) that the use of PCM/PM/Bi-phase modulation is justified when a distinct carrier component is required and only for bit rates below 2 Mbps;

recommends

(1) that CCSDS agencies use PCM/PM/Bi-phase modulation direct on the carrier for medium rate telecommand data transmission;

(2) that CCSDS agencies provide medium telecommand bit rates in the range $R = 4000*2^n$ where n=1…,6.

2.4.8 MAXIMUM PERMISSIBLE SYMBOL ASYMMETRY FOR DIGITAL SIGNALS AT THE INPUT TO THE RF MODULATOR

The CCSDS,

considering

(a) that symbol asymmetry [1, 2] (also referred to as mark-to-space ratio) results in unwanted spectral components in the spacecraft's transmitted RF signal;

(b) that such unwanted spectral components can cause harmful interference to other users of the frequency band;

(c) that for a wide range of symbol [3] rates, current technology permits control of the symbol asymmetry such that these components can be reduced to a level of -60 dBc or lower;

(d) that, in addition to unwanted spectral components, symbol asymmetry results in data power and matched filter losses which should be minimized;

(e) that rise and fall time of digital circuits sets a limit on achievable symbol asymmetry;

recommends

that the symbol asymmetry [1, 2] shall not exceed 0.2 %.

NOTES:

1. **Definition of:** $\textit{Symbol Asymmetry} = \frac{|\ \textit{long symbol} - \textit{short symbol}\ |}{\textit{long symbol} + \textit{short symbol}}$;

2. **Symbol asymmetry shall be measured at 50% of the peak-to-peak amplitude point.**

3. **A symbol is not unambiguously defined in the literature. For purposes of this Recommendation, a symbol shall be equivalent to:**

   - **a bit or an encoded bit or a chip in the case of NRZ waveforms;**
   - **half a bit or half an encoded bit or half an encoded chip in the case of Bi-ϕ waveforms;**
   - **half of the clock cycle for a squarewave subcarrier.**

2.4.12A MAXIMUM PERMISSIBLE PHASE AND AMPLITUDE IMBALANCES FOR SUPPRESSED CARRIER (BPSK/QPSK) RF MODULATORS FOR SPACE-TO-EARTH LINKS, CATEGORY A

The CCSDS,

considering

(a) that suppressed carrier modulation (PSK) is recommended by CCSDS [401 (2.3.2) B-1] for spacecraft telemetry transmissions in the 2 and 8 GHz bands when residual carrier modulation would exceed PFD limits on the Earth's surface;

(b) that the presence of unwanted discrete spectral lines in the received spectrum may degrade the receiver's performance;

(c) that phase and amplitude imbalances in the modulated RF carrier, caused by imperfections in the PSK modulator, contribute to the generation of a spurious spectral line at the carrier's frequency which can be detrimental to the performance of a PSK system and which may exceed PFD constraints;

(d) that a phase imbalance of less than 2 degrees and an amplitude imbalance of less than 0.2 dB will result in a carrier suppression of between 25 and 42 dB;

(e) that for near-Earth missions where one can have excessive data margin, the degradation due to the cross-talk caused by the phase and amplitude imbalances in a balanced QPSK system can be tolerated up to 0.4 dB;

(f) that although the phase and amplitude imbalances in a balanced QPSK modulator contribute to the generation of cross-talk between channels which can be detrimental to the system performance, the actual limiting factor is the PFD constraints for near-Earth missions where excessive data margin can be available;

recommends

that the modulator's phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in a suppressed carrier RF modulation system, provided however that the carrier suppression shall always be 30 dB or more.

2.4.12B MAXIMUM PERMISSIBLE PHASE AND AMPLITUDE IMBALANCES FOR SUPPRESSED CARRIER (BPSK/QPSK) RF MODULATORS FOR SPACE-TO-EARTH LINKS, CATEGORY B

The CCSDS,

considering

(a) that suppressed carrier modulation (PSK) is recommended by CCSDS [401 (2.3.2) B-1] for spacecraft telemetry transmissions in the 2 and 8 GHz Category B bands;

(b) that the presence of unwanted discrete spectral lines in the received spectrum may degrade the receiver's performance;

(c) that phase and amplitude imbalances in the modulated RF carrier, caused by imperfections in the PSK modulator, contribute to the generation of a spurious spectral line at the carrier's frequency which can be detrimental to the performance of a PSK system;

(d) that, for a balanced QPSK system of which the data rate and the power are the same for both In-phase (I) and Quadrature (Q) channels, the phase imbalance between channels caused by a deviation from the ideal 90-degree separation occurs when the phase shifter at the transmitter and/or the receiver is no longer operated in the linear region;

(e) that, for a balanced QPSK system, the phase and amplitude imbalances in the modulated RF carrier as well as the phase imbalance between channels contribute to the generation of cross-talk between channels through either a failure of maintaining the inter-channel orthogonality or an imperfect carrier tracking, which can be detrimental to the system performance;

(f) that a phase imbalance of less than 2 degrees and an amplitude imbalance of less than 0.2 dB will result in a carrier suppression of between 25 and 42 dB;

(g) that, for deep space missions with small data margins, the degradation due to the cross-talk caused by the phase and amplitude imbalances can be tolerated up to 0.35 dB;

recommends

(1) that the modulator's phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in order for a BPSK system to have a degradation of 0.25 dB or less at bit error rate of 10^{-3};

(2) that the modulator's phase imbalance with unbalanced modulators as well as the interchannel phase imbalance shall not exceed 2 degrees and the amplitude imbalance shall not exceed 0.2 dB in order for a balanced QPSK system to have a degradation of 0.35 dB or less at bit error rate of 10^{-3}.

2.4.14A ALLOWABLE VALUES FOR TELEMETRY SUBCARRIER FREQUENCY-TO-SYMBOL RATE RATIOS FOR PCM/PSK/PM MODULATION IN THE 2 AND 8 GHz BANDS, CATEGORY A

The CCSDS,

considering

(a) that, for Category A missions, a PCM/PSK/PM modulation scheme with a sinewave subcarrier is typically used for transmission of low data rates;

(b) that integer subcarrier frequency-to-symbol rate ratios (n) result in a data spectral density minimum around the carrier frequency;

(c) that the subcarrier frequency-to-symbol rate ratio (n) should be minimized to avoid unnecessary occupation of the frequency spectrum in accordance with Recommendation 401 (3.3.4) B-1;

(d) that the lowest practicable value of n can be determined by the amount of acceptable interference from the data spectrum (I) into the carrier tracking loop bandwidth (B_L);

(e) that, for Category A missions, a 0.3 dB degradation in the symbol detection process shall not be exceeded, which requires a 15 dB Carrier-to-Noise ratio (C/N) in the carrier tracking loop, when using CCSDS concatenated coding schemes;

(f) that any additional degradation, due to data interference in the carrier tracking loop, shall be insignificant for which a C/I ratio greater than 20 dB is considered adequate;

(g) that, for small ratios of symbol rate-to-carrier tracking loop bandwidth, the modulation index has to be adjusted accordingly in order to achieve the required loop SNR resulting in a nearly constant C/I versus B_L/R_S;

(h) that, in the presence of only one telemetry signal, a small value of n (n = 4) is generally sufficient to obtain the required performance under typical operating conditions for subcarrier frequencies above 60 kHz;

(i) that for higher symbol rates, the presence of telecommand feed-through and/or ranging signals may require the selection of a slightly higher value of n;

(j) that CCSDS Recommendation 2.4.3 provides guidance regarding the use of subcarriers in low bit rate residual carrier telemetry systems;

recommends

(1) that the subcarrier frequency-to-symbol rate ratio, n, be an integer value;

(2) that a subcarrier frequency-to-symbol rate ratio of 4 be selected for subcarrier frequencies above 60 kHz unless *recommends (3)* applies;

(3) that, in the case of spectral overlaps with other signal components, the minimum integer value of n be selected to permit no more than a 0.3 dB degradation in the symbol detection process.

2.4.14B ALLOWABLE VALUES FOR TELEMETRY SUBCARRIER FREQUENCY-TO-SYMBOL RATE RATIOS FOR PCM/PSK/PM MODULATION IN THE 2 AND 8 GHz BANDS, CATEGORY B

The CCSDS,

considering

(a) that, for Category B missions, a PCM/PSK/PM modulation scheme with a squarewave subcarrier is typically used for transmission of low data rates;

(b) that integer subcarrier frequency-to-symbol rate ratios (n) result in a data spectral density minimum around the carrier frequency;

(c) that the subcarrier frequency-to-symbol rate ratio (n) should be minimized to avoid unnecessary occupation of the frequency spectrum in accordance with Recommendation 401 (3.3.4) B-1;

(d) that the lowest practicable value of n can be determined by the amount of acceptable interference from the data spectrum (I) into the carrier tracking loop bandwidth (B_L);

(e) that, for Category B missions, a 0.1 dB degradation in the symbol detection process shall not be exceeded, which requires an 18 dB Carrier-to-Noise ratio (C/N) in the carrier tracking loop, when using CCSDS concatenated coding schemes;

(f) that any additional degradation, due to data interference in the carrier tracking loop, shall be insignificant for which a C/I ratio greater than 25 dB is considered adequate;

(g) that, for small ratios of symbol rate-to-carrier tracking loop bandwidth, the modulation index has to be adjusted accordingly in order to achieve the required loop SNR resulting in a nearly constant C/I versus B_L/R_S;

(h) that, in the presence of only one telemetry signal, a small value of n (n = 5) is generally sufficient to obtain the required performance under typical operating conditions for subcarrier frequencies above 60 kHz;

(i) that for higher symbol rates, the presence of telecommand feed-through and/or ranging signals may require the selection of a slightly higher value of n;

(j) that CCSDS Recommendation 2.4.3 provides guidance regarding the use of subcarriers in low bit rate residual carrier telemetry systems;

recommends

(1) that the subcarrier frequency-to-symbol rate ratio, n, be an integer value;

(2) that a subcarrier frequency-to-symbol rate ratio of 5 be selected for subcarrier frequencies above 60 kHz unless *recommends (3)* applies;

(3) that, in the case of spectral overlaps with other signal components, the minimum integer value of n be selected to permit no more than a 0.1 dB degradation in the symbol detection process.

2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY A

The CCSDS,

considering

(a) that Recommendation 3.3.4 emphasizes the avoidance of a PCM/PSK/PM [subcarrier] modulation scheme whenever possible;

(b) that data modulated on a residual carrier have spectral components which fall into the carrier tracking loop's bandwidth reducing the Carrier-to-Noise ratio (C/N);

(c) that the level of interference is a function of the carrier tracking loop's bandwidth (B_L), the symbol rate (R_S), and the modulation index (m);

(d) that a 0.3 dB degradation in the symbol detection process should not be exceeded requiring a Carrier-to-Noise (C/N) ratio in the carrier tracking loop of 10 dB (uncoded case) or 15 dB (CCSDS concatenated coded case);

(e) that any additional degradation resulting from data interference in the carrier tracking loop must be insignificant requiring a Carrier-to-Interference (C/I) ratio greater than 15 dB (uncoded case) and 20 dB (CCSDS concatenated coded case);

recommends

(1) that, when no coding is employed, Figure 2.4.15A-1 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L) where PCM/PM/Bi-ϕ modulation is not permitted;

(2) that, when CCSDS Concatenated coding is employed, Figure 2.4.15A-2 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L), where PCM/PM/Bi-ϕ modulation is not permitted.

2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY A (Continued)

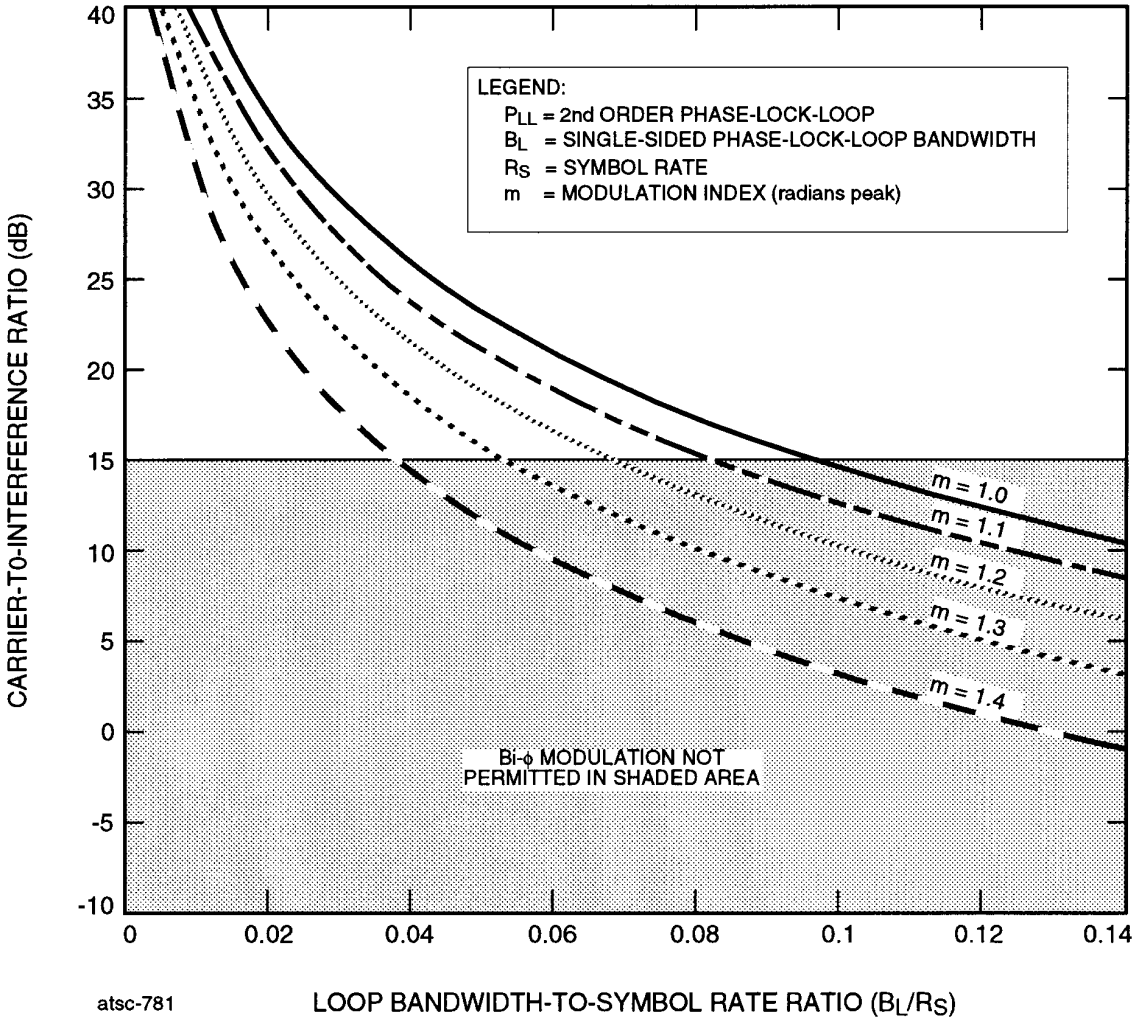

FIGURE 2.4.15A-1: OPERATING REGION FOR USE OF PCM/PM/Bi-ϕ MODULATION WHEN NO CODING IS EMPLOYED

2.4.15A MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY A (Continued)

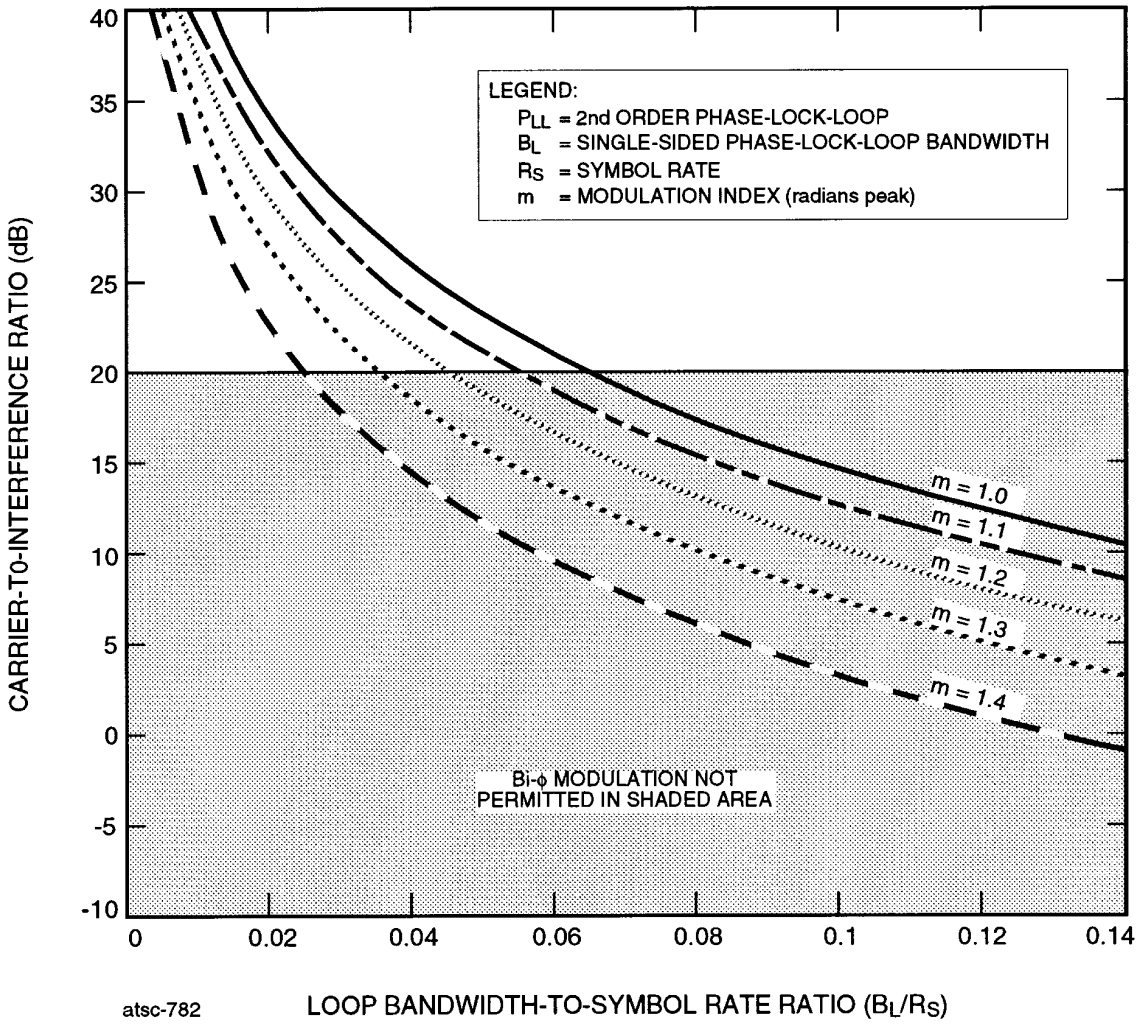

FIGURE 2.4.15A-2: OPERATING REGION FOR USE OF PCM/PM/Bi-ϕ MODULATION WHEN CCSDS CONCATENATED CODING IS EMPLOYED

2.4.15B MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY B

The CCSDS,

considering

(a) that Recommendation 3.3.4 emphasizes the avoidance of a PCM/PSK/PM [subcarrier] modulation scheme whenever possible;

(b) that data modulated on a residual carrier have spectral components which fall into the carrier tracking loop's bandwidth reducing the Carrier-to-Noise ratio (C/N);

(c) that the level of interference is a function of the carrier tracking loop's bandwidth (B_L), the symbol rate (R_S), and the modulation index (m);

(d) that a 0.1 dB degradation in the symbol detection process should not be exceeded requiring a Carrier-to-Noise (C/N) ratio in the carrier tracking loop of 12 dB (uncoded case) or 18 dB (CCSDS concatenated coded case);

(e) that any additional degradation resulting from data interference in the carrier tracking loop must be insignificant requiring a Carrier-to-Interference (C/I) ratio greater than 17 dB (uncoded case) and 25 dB (CCSDS concatenated coded case);

recommends

(1) that, when no coding is employed, Figure 2.4.15B-1 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L) where PCM/PM/Bi-ϕ modulation is not permitted;

(2) that, when CCSDS Concatenated coding is employed, Figure 2.4.15B-2 should be used for determining symbol rates (R_S), relative to loop bandwidth (B_L), where PCM/PM/Bi-ϕ modulation is not permitted.

2.4.15B MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY B (Continued)

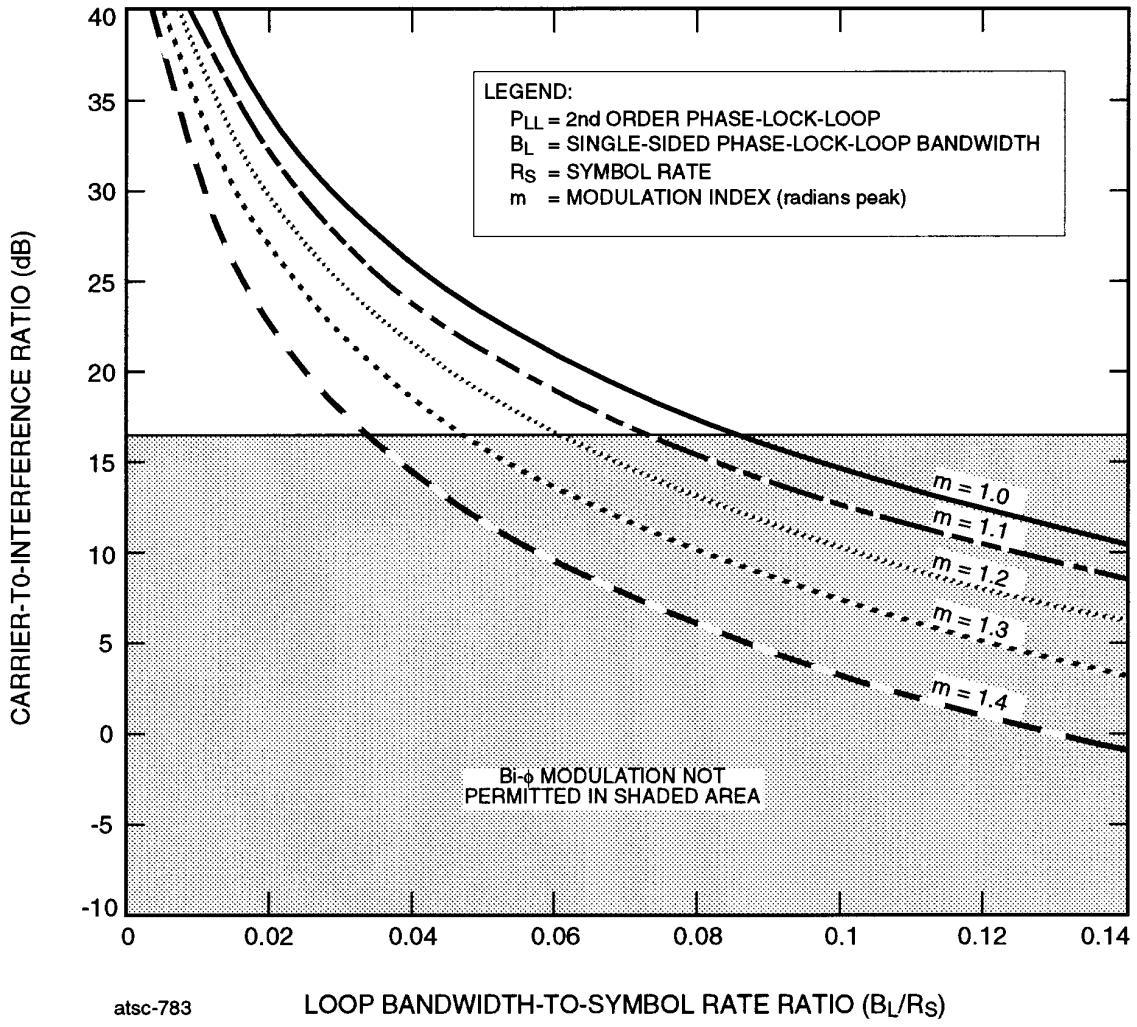

FIGURE 2.4.15B-1: OPERATING REGION FOR USE OF PCM/PM/Bi-ϕ MODULATION WHEN NO CODING IS EMPLOYED

2.4.15B MINIMUM SYMBOL RATE FOR PCM/PM/Bi-ϕ MODULATION ON A RESIDUAL RF CARRIER, CATEGORY B (Continued)

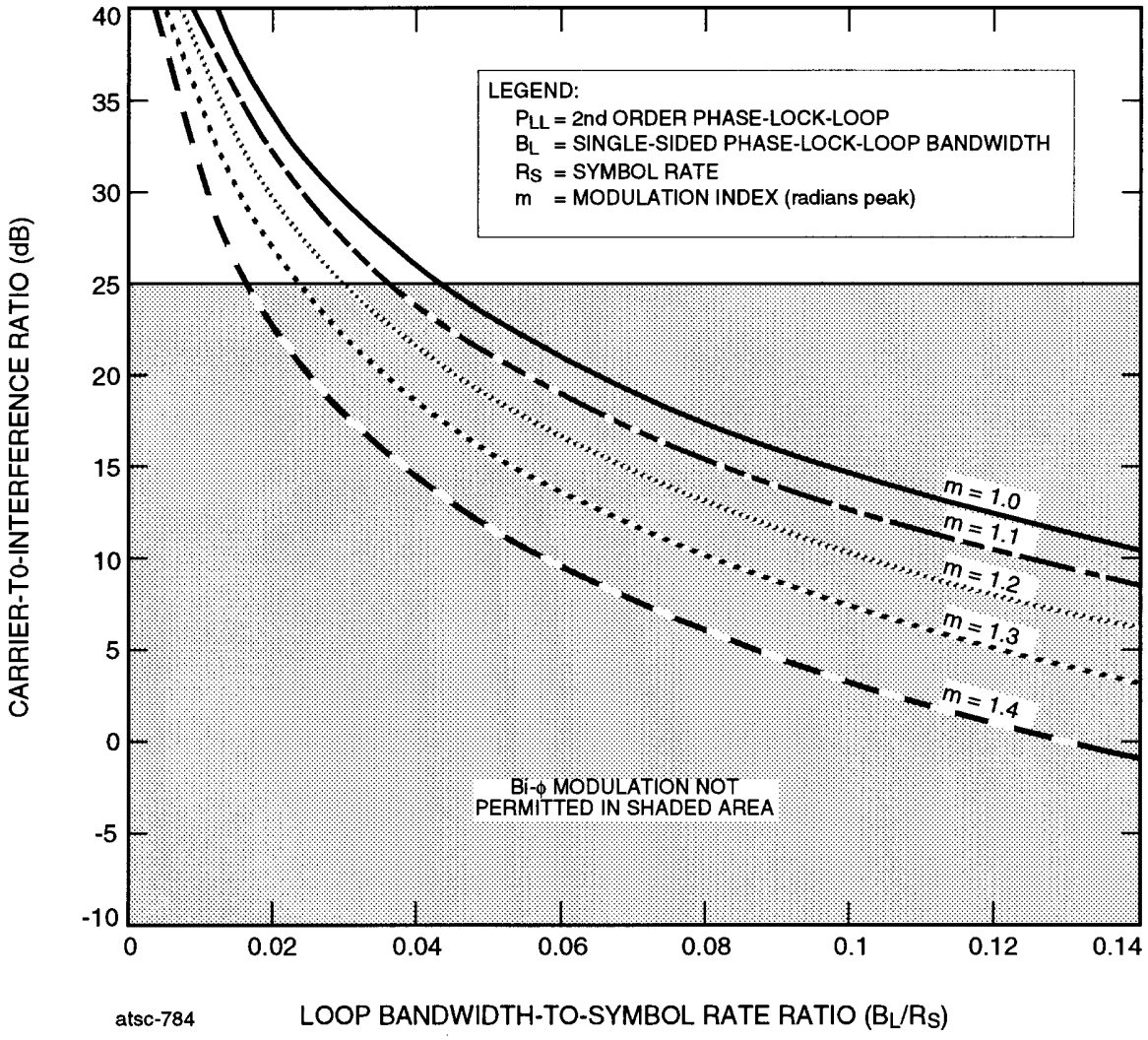

FIGURE 2.4.15B-2: OPERATING REGION FOR USE OF PCM/PM/Bi-ϕ MODULATION WHEN CCSDS CONCATENATED CODING IS EMPLOYED

2.4.16 MAXIMUM PERMISSIBLE SPURIOUS EMISSIONS

The CCSDS,

considering

(a) that spurious emissions (ITU-RR-139) in the form of spectral lines can cause harmful interference to receiving stations operating in the allocated or adjacent frequency bands;

(b) that such spurious emissions are caused by technological imperfections in the transmitting station, such as asymmetry of the baseband modulating waveform and crosstalk of the operating frequencies on the electronic power conditioners;

(c) that current technology permits reduction of these spectral components to -60 dBc or lower;

(d) that protection criteria specified for neighboring *radiocommunication services* may require additional reduction of spectral components;

(e) that filtering can be applied if further reduction in the level of spectral components is required;

recommends

that the total power contained in any single spurious emission shall not exceed -60 dBc [1].

NOTE:

1. dBc is measured with respect to the unmodulated carrier level's total power.

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B

The CCSDS,

considering

(a) that Very Long Baseline Interferometry (VLBI) measurement allow determination of geometric delay for space radio sources by the simultaneous reception and processing of radio signals at two stations;

(b) that using the VLBI geometric delay measurements from two stations, the angular position of a spacecraft can be accurately determined for navigational purposes;

(c) that the VLBI technique requires differencing phase measurements of sinusoidal tones or harmonics (known as Differential One-way Ranging [DOR] tones), modulated on the spacecraft's downlink RF carrier, which have been acquired at two (or more) stations;

(d) that VLBI accuracy depends upon a priori knowledge of both the length and orientation of the baseline vector between the stations, the station clock drift, and the media delays;

(e) that measurement errors can be greatly reduced by observing a quasar or Extra-Galactic Radio source (EGRS), that is angularly near the spacecraft, and then differencing the delay measured from the ERGS observation with the delay measured from observing the spacecraft (ΔDOR);

(f) that the spacecraft delay measurement's precision depends upon the received power (P_{DOR}) in the two most widely spaced DOR tones, f_{BW} Hz apart, as shown in the error relationship:

$$\varepsilon_\tau = \left[f_{BW} \sqrt{4\pi \frac{P_{DOR}}{N_0} T_{obs}} \right]^{-1} \text{ seconds, where:}$$

f_{BW} = DOR tone spanned bandwidth (Hz)
T_{obs} = observation time (seconds);

(g) that a narrow spanned bandwidth is needed for integer cycle ambiguity resolution because the ΔDOR time delay ambiguity equals the reciprocal of the minimum spanned bandwidth;

(h) that, contrary to *considering (g)*, a wide spanned bandwidth is needed for high measurement accuracy;

(i) that doubling the spanned bandwidth of spacecraft DOR tones, while holding the other parameters fixed, will reduce errors resulting from low spacecraft SNR, low quasar SNR, and instrument phase ripple by half;

(j) that delay ambiguities in observables generated from wider bandwidths are resolved successively by using delay estimates from the narrower spanned bandwidths;

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Cont.)

(k) that a typical ΔDOR error budget is dominated by errors due to low quasar SNR, quasar position uncertainty, instrument phase ripple, and the troposphere;

(l) that EGRS delay measurement precision and instrument errors vary as $1/f_{BW}$;

(m) that direct phase modulation of a sinewave tone on the downlink RF carrier is more spectrum efficient than squarewave modulation and allows appropriate choices of spanned bandwidth and tone power;

(n) that the received spacecraft DOR tone power must be adequate for tone detection, with the threshold approximately determined by:

$$Threshold = \left[\frac{P_{DOR}}{N_0} \right]$$ = 13 dB • Hz if no carrier aiding is used;

(o) that the DOR tone threshold reduces to:

$$Threshold = \left[\frac{P_{DOR}}{N_0} \right]$$ = 1 dB • Hz provided that the spacecraft RF carrier's SNR is greater than 13 dB and that the extracted carrier phase is used to aid in tracking the DOR tone whose frequency is a coherent submultiple of the spacecraft's RF carrier frequency;

(p) that the stability of the spacecraft's RF carrier stability, over a 1-second averaging time, must be adequate for signal detection;

(q) that the stability of the spanned bandwidth of the DOR tones, over a 1000-second averaging time, must be adequate for converting the measured phase difference to time delay;

(r) that the *Space Research service* frequency allocation for Category B missions is 10 MHz in the 2 GHz band, 50 MHz in the 8 GHz band, 400 MHz in the 32 GHz band, and 1 GHz in the 37 GHz band;

(s) that quasar flux is reduced and system noise temperature is higher at 32 and 37 GHz as compared to 8 GHz;

recommends

(1) that DOR tone be sinewaves;

(2) that either direct tone detection or carrier-aided tone detection be used;

(3) that DOR tones be coherent with the downlink RF carrier frequency if carrier-aided detection is used;

(4) that one DOR tone pair be used in the 2 GHz band, two DOR tone pairs be used in the 8 GHz band, and three DOR tone pairs be used in the 32 and 37 GHz bands;

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Cont.)

(5) that the approximate DOR tone frequencies used in each band be those in Table 2.5.6-1;

TABLE 2.5.6-1: RECOMMENDED DOR TONES

Space-to-Earth Frequency Band	Number of DOR Tones	Approximate DOR Tone Frequencies (± 10%)
2 GHz	1	4 MHz
8 GHz	2	4 MHz and 20 MHz
32 & 37 GHz	3	4 MHz, 20 MHz, and 120 MHz

(6) that, if spacecraft DOR data are to be acquired in the one-way mode, the spacecraft's oscillator stability shall be:

$\Delta f/f \leq 4.0 \times 10^{-10}$ at 2 GHz,
$\Delta f/f \leq 1.0 \times 10^{-10}$ at 8 GHz,
$\Delta f/f \leq 0.3 \times 10^{-10}$ at 32 and 37 GHz

where: $\Delta f/f$ denotes the spacecraft oscillator's frequency variations;

(7) that the frequency stability of the spanned bandwidth, f_{BW}, of the DOR tones must satisfy:

$\Delta f_{BW}/f_{BW} \leq 1 \times 10^{-9}$ over a 1000-second averaging time

where: Δf_{BW} denotes spanned bandwidth variations due to on-board oscillator instabilities.

FREQUENCY UTILIZATION RECOMMENDATION SUMMARY

REC. NO.	RECOMMENDED CHARACTERISTICS	RECOMMENDATION SUMMARY
3.1.1	2 GHz System Parameters	Efficient use of 2 GHz bands for space operation.
3.1.2A	10 MHz Occupied BW	Max Cat A telemetry bandwidth in 8 GHz band.
3.1.3A		Deleted.
3.1.4A	Constraints	Cat A constraints on use of 14-17 GHz bands.
3.1.5B		Deleted.
3.1.6B	Channel Frequencies	Cat B channel frequency plan for 2, 7, 8, 32, 34 GHz.

POWER LIMITATIONS RECOMMENDATION SUMMARY

REC. NO.	RECOMMENDED CHARACTERISTICS	RECOMMENDATION SUMMARY
3.2.1A	EIRP Levels	Cat A Limitations on earth-to-space link.

SPACECRAFT SYSTEMS RECOMMENDATION SUMMARY

REC. NO.	RECOMMENDED CHARACTERISTICS	RECOMMENDATION SUMMARY
3.6.1A	Power Spectral Density	Interference reduction in the 2200-2290 MHz bands.
3.6.2A	Power Spectral Density	Constraints on space-to-space links.

3.1.1 EFFICIENT UTILIZATION OF THE 2 GHz BANDS FOR SPACE OPERATION

The CCSDS,

considering

(a) that the frequency bands 2025–2110 and 2200–2290 MHz are shared co-equally by the Space Research, Space Operation, and Earth Exploration Satellite services;

(b) that bands allocated to the Space Operation service may be used for space tracking, space telemetry, and space telecommand (TTC) by other space services;

(c) that the definition of the Space Operation service (SI.23) postulates that these TTC activities by other space services normally be carried out in their service bands;

(d) that the bands 2025–2110 and 2200–2290 MHz, which are already now densely occupied, are of prime importance for space science missions of CCSDS agencies and will remain so for many years to come as no comparable alternative frequency allocations are available;

recommends

that, in order to make maximum use of these bands for satellite missions of all kinds, appropriate technical and operational constraints be observed, particularly:

i Geostationary space systems of space services other than the space science services[1] which are designed to operate in mission bands other than 2025–2110 and 2200–2290 MHz, but which utilize TTC systems within these bands, shall limit the use of such TTC systems to a single frequency pair per satellite and to launch, orbit insertion, and emergency operations.

ii TTC systems for geostationary satellites of space services other than the space science services should be designed in accordance with the general characteristics as contained in Table 3.1.1-1.

iii Non-geostationary satellites of services other than the space science services avoid using these bands for TTC.

[1] Space Science Services include the Space Research, Space Operations, Earth Exploration Satellite and Meteorological Satellite Services

3.1.1 EFFICIENT UTILIZATION OF THE 2 GHz BANDS FOR SPACE OPERATION (Continued)

TABLE 3.1.1-1

TYPICAL SYSTEM PARAMETERS FOR SPACE OPERATION OF GEOSTATIONARY SATELLITES AT 2 GHz

MODE	SYSTEM PARAMETERS	
Reception at Earth station	Telemetry bandwidth	100 kHz
	Tracking bandwidth	400 kHz
	G/T, Earth stations	20 dB/K
Transmission from Earth stations	Telecommand bandwidth	100 kHz
	Tracking bandwidth	400 kHz
	EIRP, Earth station	65 dBW

3.1.2A USE OF THE 8450 — 8500 MHz BAND FOR SPACE RESEARCH, CATEGORY A

The CCSDS,

considering

(a) that the Radio Regulations permit the use of the 8450–8500 MHz band for Category A and Category B space missions;

(b) that the band is one of only three primary allocations to the Space Research service below 40 GHz;

(c) that the band, because of crowding at 2200–2290 MHz, is particularly suitable for distant missions such as to the Libration points;

(d) that the 8400–8450 MHz band is allocated for and restricted to Category B missions;

(e) that the 14.0–15.35 GHz and 37–38 GHz bands have been identified by SFCG[1] as appropriate for Category A missions requiring wide (greater than 10 MHz) bandwidth;

recommends

(1) that the 8450–8500 MHz band be used for Category A missions requiring an occupied bandwidth of up to 10 MHz per mission;

(2) that the band be used in particular for the missions to the Libration points with bandwidth requirements up to 10 MHz;

(3) that utmost care be taken in the assignment of frequencies in this band in order to make optimum use of the limited bandwidth available to Category A missions and that the maximum bandwidth, postulated in *recommends (1)* be strictly respected;

(4) that the 8450–8500 MHz band should not be used for Category B missions.

[1] See SFCG recommendation 5-1R5.

3.1.3A USE OF THE 13.25 — 15.35 GHz BANDS FOR SPACE RESEARCH, CATEGORY A

This recommendation has been deleted (CCSDS resolution MC-S98-3).

3.1.5B USE OF THE 31.8 — 34.7 GHz BANDS FOR SPACE RESEARCH, CATEGORY B

This recommendation has been deleted (CCSDS resolution MC-S98-3).

3.1.6B CHANNEL FREQUENCY PLAN FOR 2, 7, 8, 32, AND 34 GHZ, CATEGORY B

The CCSDS,

considering

(a) that channel frequency plans for Category B missions exist for the 2, 7, 8, 32, and 34 GHz bands;

(b) that the sets of channel frequency pairs in these existing plans are based upon the recommended turnaround ratios;

(c) that members of the Space Frequency Coordination Group (SFCG) have resolved to select frequencies for their Category B missions from the existing channel frequency plans;

(d) that most past, existing, and planned Category B missions have assigned frequencies that were selected on the basis of these existing channel frequency plans;

(e) that CCSDS agencies conducting Category B missions have coordinated the selection of frequencies from those embodied in the existing channel frequency plans in order to avoid interference between missions;

recommends

(1) that CCSDS agencies select frequencies for their Category B missions operating in the 2, 7, 8, 32, and 34 GHz bands from the channel frequency plan contained in Table 3.1.6B-1;

(2) that frequency selection be coordinated with an appropriate organization, such as the SFCG, to ensure the orderly use of the channel frequency plan.

TABLE 3.1.6B-1 - Channel Frequencies for Category B (Deep-Space) Missions

BAND (GHz):	2 E-S	2 S-E	7 E-S	8 S-E	32 S-E	34 E-S
FACTOR:	221	240	749	880	3344	3599
CHANNEL		F2DN				
1	* 2108.878858	2290.185185	7147.286265	* 8397.345679	# 31909.913580	# 34343.235339
2	* 2109.219908	2290.555556	7148.442132	* 8398.703706	# 31915.074083	# 34348.789361
3	* 2109.560957	2290.925926	7149.597994	8400.061729	# 31920.234571	# 34354.343368
4	* 2109.902006	2291.296296	7150.753857	8401.419752	# 31925.395059	# 34359.897374
5	2110.243056	2291.666667	7151.909724	8402.777780	31930.555562	34365.451396
6	2110.584105	2292.037037	7153.065587	8404.135803	31935.716050	34371.005402
7	2110.925154	2292.407407	7154.221450	8405.493826	31940.876538	34376.559408
8	2111.266204	2292.777778	7155.377316	8406.851853	31946.037042	34382.113431
9	2111.607253	2293.148148	7156.533179	8408.209876	31951.197530	34387.667437
10	2111.948303	2293.518519	7157.689045	8409.567903	31956.358033	34393.221460
11	2112.289352	2293.888889	7158.844908	8410.925927	31961.518521	34398.775466
12	2112.630401	2294.259259	7160.000771	8412.283950	31966.679009	34404.329472
13	2112.971451	2294.629630	7161.156637	8413.641977	31971.839512	34409.883494
14	2113.312500	2295.000000	7162.312500	8415.000000	31977.000000	34415.437500
15	2113.653549	2295.370370	7163.468363	8416.358023	31982.160488	34420.991506
16	2113.994599	2295.740741	7164.624229	8417.716050	31987.320991	34426.545528
17	2114.335648	2296.111111	7165.780092	8419.074073	31992.481479	34432.099534
18	2114.676697	2296.481481	7166.935955	8420.432097	31997.641967	34437.653540
19	2115.017747	2296.851852	7168.091821	8421.790124	32002.802470	34443.207563
20	2115.358796	2297.222222	7169.247684	8423.148147	32007.962958	34448.761569
21	2115.699846	2297.592593	7170.403550	8424.506174	32013.123462	34454.315592

Notes: Channel frequencies marked " * " are not within the Category B band allocation.

Channel frequencies marked " # " may be used in conjunction with the corresponding channel in a lower frequency band if that channel is not marked by " * ".

F2DN = N(10/27) + 2295 MHz, where N is in the range -13 to +28 for this Table. The value of F2DN is rounded to the nearest Hz. Frequencies in the 2 GHz E-S band are then computed and rounded to the nearest Hz. Channel numbers are equal to N + 14. Frequencies in other bands are derived from the 2 GHz E-S frequencies by using the corresponding ratio of frequency factors, and then rounding to the nearest Hz.

TABLE 3.1.6B-1 (continued): Channel Frequencies for Category B (Deep-Space) Missions

BAND (GHz):	2 E-S	2 S-E	7 E-S	8 S-E	32 S-E	34 E-S
FACTOR:	221	240	749	880	3344	3599
CHANNEL		F2DN				
22	2116.040895	2297.962963	7171.559413	8425.864197	32018.283950	34459.869598
23	2116.381944	2298.333333	7172.715276	8427.222220	32023.444438	34465.423604
24	2116.722994	2298.703704	7173.871143	8428.580248	32028.604941	34470.977626
25	2117.064043	2299.074074	7175.027006	8429.938271	32033.765429	34476.531632
26	2117.405092	2299.444444	7176.182868	8431.296294	32038.925917	34482.085639
27	2117.746142	2299.814815	7177.338735	8432.654321	32044.086420	34487.639661
28	2118.087191	* 2300.185185	7178.494597	8434.012344	# 32049.246908	# 34493.193667
29	2118.428241	* 2300.555556	7179.650463	8435.370371	# 32054.407411	# 34498.747689
30	2118.769290	* 2300.925926	7180.806327	8436.728395	# 32059.567899	# 34504.301695
31	2119.110339	* 2301.296296	7181.962190	8438.086418	# 32064.728387	# 34509.855701
32	2119.451389	* 2301.666667	7183.118056	8439.444445	# 32069.888891	# 34515.409724
33	2119.792438	* 2302.037037	7184.273919	8440.802468	# 32075.049379	# 34520.963731
34	* 2120.133487	* 2302.407407	7185.429782	8442.160491	# 32080.209867	# 34526.517737
35	* 2120.474537	* 2302.777778	7186.585648	8443.518518	# 32085.370370	# 34532.071759
36	* 2120.815586	* 2303.148148	7187.741511	8444.876542	# 32090.530858	# 34537.625765
37	* 2121.156636	* 2303.518519	7188.897377	8446.234569	# 32095.691361	# 34543.179787
38	* 2121.497685	* 2303.888889	* 7190.053240	8447.592592	# 32100.851849	# 34548.733793
39	* 2121.838734	* 2304.259259	* 7191.209103	8448.950615	# 32106.012337	# 34554.287799
40	* 2122.179784	* 2304.629630	* 7192.364969	* 8450.308642	# 32111.172840	# 34559.841822
41	* 2122.520833	* 2305.000000	* 7193.520832	* 8451.666665	# 32116.333328	# 34565.395828
42	* 2122.861882	* 2305.370370	* 7194.676696	* 8453.024689	# 32121.493816	# 34570.949834

Notes: Channel frequencies marked " * " are not within the Category B band allocation.

Channel frequencies marked " # " may be used in conjunction with the corresponding channel in a lower frequency band if that channel is not marked by " * ".

F2DN = N(10/27) + 2295 MHz, where N is in the range -13 to +28 for this Table. The value of F2DN is rounded to the nearest Hz. Frequencies in the 2 GHz E-S band are then computed and rounded to the nearest Hz. Channel numbers are equal to N + 14. Frequencies in other bands are derived from the 2 GHz E-S frequencies by using the corresponding ratio of frequency factors, and then rounding to the nearest Hz.

3.2.1A LIMITATIONS ON EARTH-TO-SPACE LINK POWER LEVELS, CATEGORY A

The CCSDS,

considering

(a) that spectral occupation of frequency bands used by space agencies is increasing rapidly;

(b) that in many cases the same frequencies will be shared by several spacecraft;

(c) that the 2025–2110 MHz band is also shared with space-to-space links from data relay satellites to user satellites, which are limited to relatively small power levels by the provisions of RR S21.16 and are consequently particularly susceptible to interference;

(d) that excessive EIRP from Earth stations will make intra-service frequency sharing increasingly difficult and result in inefficient use of the radio frequency spectrum;

(e) that excessive EIRP from Earth stations likewise unnecessarily complicates the coordination with terrestrial services and may in some cases increase the coordination area;

(f) that the required EIRP from an Earth station is determined by P_c/N_o, E_b/N_o, and the minimum signal level required by the spacecraft receiver;

recommends

(1) that CCSDS agencies limit the EIRP on the Earth-to-space links to that required for safe spacecraft operation by means of one or several of the following:

- CCSDS agencies avoid, whenever practicable, using high power transmitters having a fixed output but instead adjust their transmitted power level to the minimum needed to meet project requirements;

- CCSDS agencies obtain the required EIRP by using reasonable antenna diameters in order to reduce both sidelobe radiation and transmitter power (Guideline: antenna diameter/RF wavelength equal to or greater than 70);

- CCSDS agencies make Recommendation ITU-R SA.509 a requirement in antenna specifications;

(2) that spacecraft equipment designers endeavour to provide similar margins with regard to minimum P_c/N_o, minimum E_b/N_o and the minimum signal required by the spacecraft receiver.

3.6.1A INTERFERENCE REDUCTION IN THE 2200 - 2290 MHz BANDS, CATEGORY A

The CCSDS,

considering

(a) that the planned increase in the number of links in the 2 GHz bands will raise the likelihood of harmful interference;

(b) that channel coding techniques, such as the CCSDS concatenated codes, can reduce the power spectral density by more than 10 dB while lowering the susceptibility to interference;

(c) that the use of suppressed carrier modulation techniques as recommended by the CCSDS, can further reduce the power spectral density;

recommends

that the power spectral density of space radiocommunication links be reduced by using appropriate modulation techniques and channel coding in accordance with CCSDS Recommendations in order to reduce the potential for harmful interference.

3.6.2A INTERFERENCE FROM SPACE-TO-SPACE LINKS BETWEEN NON-GEOSTATIONARY SATELLITES TO OTHER SPACE SYSTEMS IN THE 2025 - 2110 AND 2200 - 2290 MHz BANDS, CATEGORY A

The CCSDS,

considering

(a) that space-to-space transmissions between two or more non-geostationary satellites shall not impose any constraints on other space transmissions (ITU-RR-750A);

(b) that the planned increase in the number of space-to-space links between non-geostationary satellites will raise the likelihood of harmful interference;

recommends

that the power spectral density of space-to-space links between any two non-geostationary satellites be reduced by using appropriate modulation techniques and channel coding in accordance with CCSDS Recommendations, in order to reduce the potential for harmful interference to space-to-Earth, Earth-to-space, and space-to-space transmissions involving at least one geostationary satellite.

COMPUTATIONAL ALGORITHMS RECOMMENDATION SUMMARY

REC. NO.	RECOMMENDED CHARACTERISTICS	RECOMMENDATION SUMMARY
4.2.1	B/W PCM/PM	Approximations for calculating.
4.2.2	B/W with sine wave subcarrier	Approximations for calculating.
4.2.3	B/W with square wave subcarrier	Approximations for calculating.

4.2.2 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SINEWAVE SUBCARRIER

The CCSDS,

considering

(a) that prior to the design of spacecraft and the assignment of frequencies, the *Occupied Bandwidth* must be known;

(b) that the *Occupied Bandwidth* is defined as the frequency band containing 99% of the emitted power (ITU-RR-147);

(c) that for PCM/PSK/PM modulation with an NRZ data format, a simple, exact closed form expression to calculate the *Occupied Bandwidth* is not available over the full range of applicable modulation indices;

(d) that an approximation having better than 10% accuracy has been developed for a representative range of modulation indices;

(e) that the *Occupied Bandwidth* can be computed with high precision using numerical integration techniques and can be plotted for easy use;

recommends

(1) that the *Occupied Bandwidth*, B, for PCM/PSK/PM with a sinewave subcarrier be estimated by:

$$B = 4n \bullet R_S \text{ for } 0.8 < m < 1.35 \text{ and } n > 7 \text{ (in Hz)}$$

where:

n	=	subcarrier frequency-to-symbol rate ratio
R_S	=	symbol rate (s/s)
m	=	modulation index (radians peak)

(2) that B for any other combination of m and n be determined by using Figure 4.2.2-1.

4.2.2 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SINEWAVE SUBCARRIER (Continued)

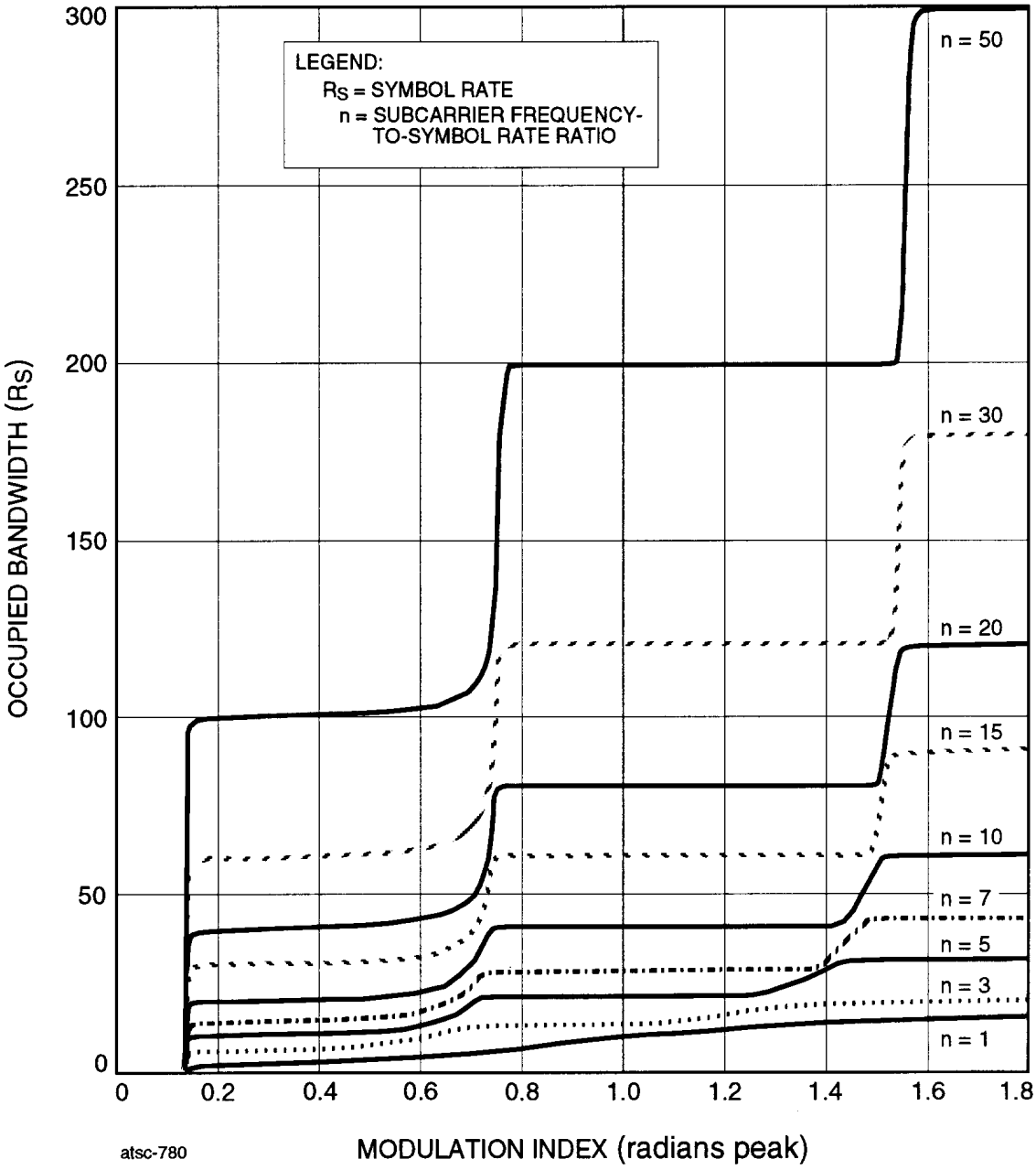

FIGURE 4.2.2-1: OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM SIGNAL WITH A SINEWAVE SUBCARRIER

4.2.3 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SQUAREWAVE SUBCARRIER

The CCSDS,

considering

(a) that prior to the design of spacecraft and the assignment of frequencies, the *Occupied Bandwidth* must be known;

(b) that the *Occupied Bandwidth* is defined as the frequency band containing 99% of the emitted power (ITU-RR-147);

(c) that for PCM/PSK/PM modulation with an NRZ data format, a simple, exact closed form expression to calculate the *Occupied Bandwidth* is not available over the full range of applicable modulation indices;

(d) that an approximation having better than 10% accuracy has been developed for a representative range of modulation indices;

(e) that the *Occupied Bandwidth* can be computed with high precision using numerical integration techniques and can be plotted for easy use;

recommends

(1) that the *Occupied Bandwidth*, B, for PCM/PSK/PM with a squarewave subcarrier be estimated by:

$$B = [(-43.2\,m^3 + 103\,m^2 - 2\,m - 1)\,n + 11] \bullet R_S \quad \text{for } m > 0.5 \text{ radians (in Hz)}$$

where:

n	=	subcarrier frequency-to-symbol rate ratio
R_S	=	symbol rate (s/s)
m	=	modulation index (radians peak)

(2) that B for any other combination of m and n be determined by using Figure 4.2.3-1.

4.2.3 COMPUTATIONAL METHOD FOR DETERMINING THE OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM MODULATION WITH A SQUAREWAVE SUBCARRIER (Continued)

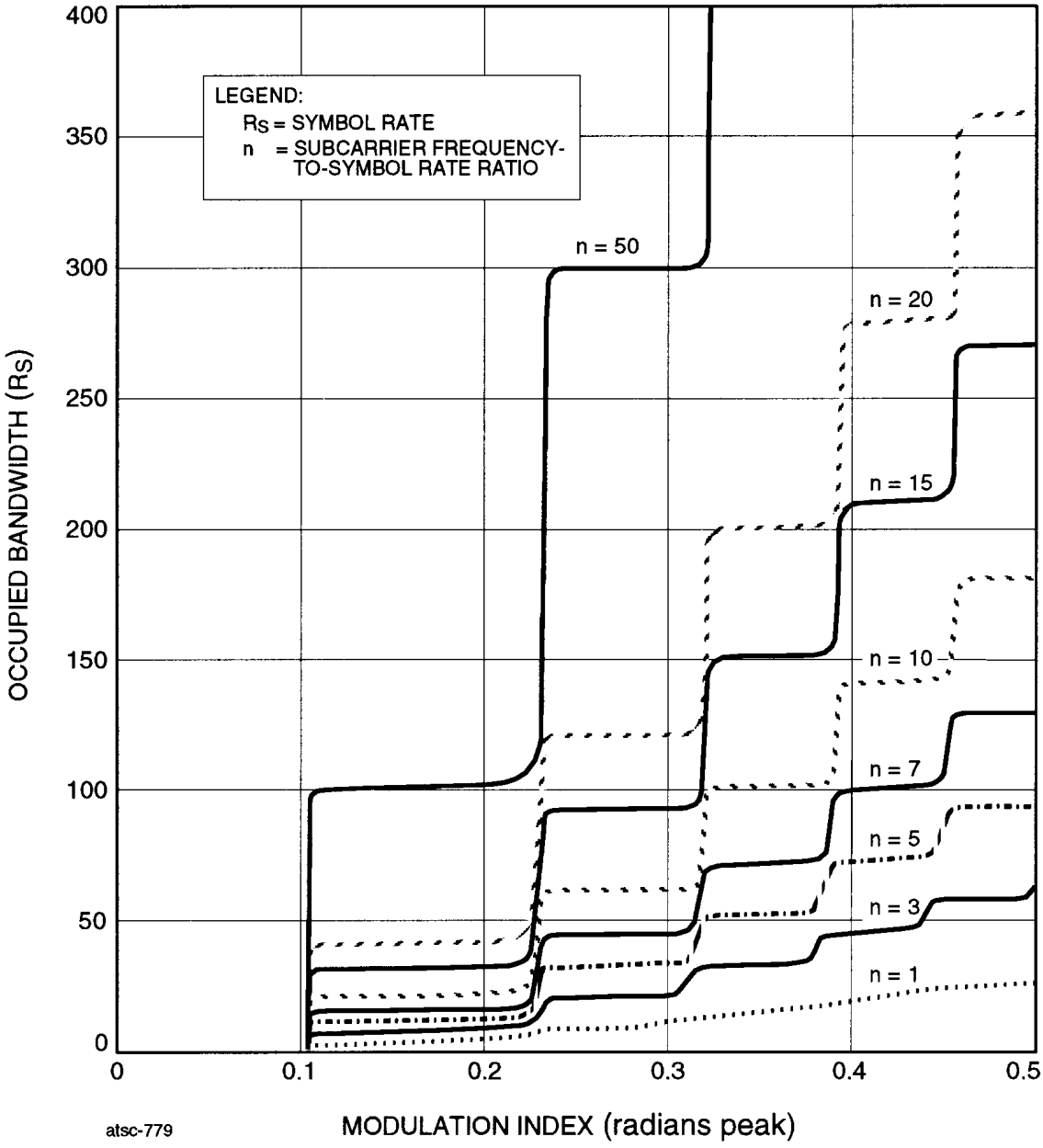

FIGURE 4.2.3-1: OCCUPIED BANDWIDTH OF UNFILTERED PCM/PSK/PM SIGNAL WITH A SQUAREWAVE SUBCARRIER